Similarity measure for quality control of dental CAD/CAM-applications

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Abstract: There is no measure for morphometric quality control of dental CAD/CAM-restorations as well as for evaluation of newly developed CAD/CAM-applications. The aim of this study was to (a) establish a 3D-measure for morphological comparisons, (b) to proof its metrical and subjective-visual validity and (c) to explore morphological features which have relevant impact on visual perception. 125 maxillary anterior teeth were chosen from a digital library of 3D data sets and compared by automatic superimposition with a best-fit method. The superimposition was analyzed by a newly defined 3-dimensional similarity measure, called shape similarity value (SSV). With this measure, similarity between symmetrical and non-symmetrical teeth was evaluated and the metrical validity was tested. Additionally, visual evaluation of tooth similarities were performed and analyzed by means of multivariate statistical procedures, to test the correspondence between metrical similarity measure and visual similarity perception. The measure clearly reproduced the similarity of contralateral teeth and the dissimilarity of teeth between different individuals. The coincidence between quantitative similarity measure and visual perception was moderate. In conclusion, the presented 3D-measure can be considered as a first substantial step towards a morphometric quality control of CAD/CAM-restorations of anterior teeth.

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Similarity measure for quality control of dental CAD/CAM-applications

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SUMMARY

There is no measure for morphometric quality control of CAD/CAM-restorations of anterior teeth as well as for the evaluation of new approaches in computer-aided design. The aim of this study was to establish a 3D-measure for morphological comparisons, to proof its metrical and subjective-visual validity and to explore morphological features which have a relevant impact on visual perception. 125 maxillary anterior teeth were chosen from a digital library of 3D data sets and compared by automatic superimposition with a best-fit method. The superimposition was analyzed by a newly defined 3-dimensional similarity measure, called shape similarity value (SSV). With this measure, similarity between symmetrical and non-symmetrical teeth was evaluated and the metrical validity was tested. Additionally, visual evaluation of tooth similarities were performed and analyzed by means of multivariate statistical procedures, to test the correspondence between metrical similarity measure and visual similarity perception. The measure clearly reproduced the similarity of contralateral teeth and the dissimilarity of teeth between different individuals. The coincidence between quantitative similarity measure and visual perception was moderate. In conclusion, the presented 3D-measure can be considered as a first substantial step towards a morphometric quality control of CAD/CAM-restorations of anterior teeth.

KEYWORDS: similarity measure; dental morphology; morphometry; CAD/CAM; multivariate analysis; quality control; aesthetics; oral rehabilitation;

Introduction

Manufacturing of dental restorations by computer assistance has become very common in the last years. However, automatic reconstruction procedures, especially in the anterior region, often produce stereotypical restorations that do not correspond to naturally shaped teeth or do not fit to the surrounding tooth morphologies. Further development in computer-aided design may overcome this drawback. For the evaluation of new approaches in computer-assisted design, a 3D-measure for morphological comparisons of anterior teeth is needed. Such a measure may also be used for the implementation in CAD/CAM systems for the purpose of internal quality control. In respect of a proper measure it is crucial to quantify the morphometrical as well as the esthetical harmony and naturalness of a reconstructed crown as demanded by experts. Besides, it is not understood which morphological features considerably determine visual perception of anterior teeth. Proper knowledge about these aspects can give orientation for both computer-aided-design and evaluation of reconstructions.

Morphometry, the process of describing dental morphology is the quantitative detection and comparing analysis of biological forms (1) which have two main components, size and shape. Concerning anterior teeth, a few common odontometrical aspects are available for their characterization and appearance. These are linear measurements (2-5), the width-to-length-ratio (6-9) and the width-to-width-ratio between teeth in the same individual (9, 10, 11). However, these metric measurements do not provide any information about the shape of tooth surfaces (12, 13). Shape refers to the structure independent of rotation, translation, or scaling (14). Information about the shape of anterior teeth in general only consists of qualitative visual description. Knowledge of such quality gives no clue how to quantify the performance of an anterior rehabilitation.

The aim of this study was to show that a new 3D-measure reproduce clearly the similarity of contralateral teeth and the dissimilarity of teeth between different individuals. The coincidence of visual perception of dental professionals and the 3D-measure should be proved. Additionally it was intended to explore morphological features which have a relevant impact on visual perception of anterior teeth.

Materials and methods

Shape Similarity Value (SSV)

125 maxillary anterior teeth were chosen from a digital library of 3D data sets (15). The labial surfaces were superimposed on each other according to a best-fit method by the program Match3D

2.5 (16). Difference images (Fig. 1) were calculated between each pair of tooth surfaces by evaluating the distances point by point in sagittal z-direction (perpendicular to the labial surface, about 50.000 surface points (k)) (16). The "shape similarity"-value (SSV) was defined as the sum of the positive volumetric deviation and the absolute negative volumetric deviation, divided by the surface area of the difference image:

$$\text{shape similarity value} = \frac{Vol_{pos} + \text{abs}(Vol_{neg})}{A_{tooth}}$$

In mathematical theory this value corresponds to a l_1-distance metric in k-dimensional vector space by $\left\| \vec{v}_{tooth1} - \vec{v}_{tooth2} \right\|_{l_1} / k$. Superimposed surfaces which are dissimilar come along with high volumetric deviations resulting in a high SSV and vice versa. With this measure, similarities of (A) symmetric (125 comparisons between contralateral teeth) and (B) non-symmetric (crosswise comparisons between teeth of different individuals, n=31 000) teeth were calculated.

Visual Perception of Tooth Morphology

In order to examine the visual perception of tooth morphology, Multidimensional Scaling (MDS) was utilized. This is a statistical technique often used for exploring similarities and dissimilarities in data (marketing, cognitive science, etc.). MDS algorithm processes data of visually rated tooth-tooth similarities and then assigns a location of each tooth in a two-dimensional Euclidean space, suitable for graphing. This graphic technique which attempts to visually display the perceptions of evaluators is called perceptual mapping. In a perceptual map, teeth positioned close to each other are seen as similar by the evaluators. Underlying dimension 1 (x-axis) and dimension 2 (y-axis) of the map are not preassigned and have to be interpreted. The dimensions represent certain features of tooth morphology which are relevant for the visual perception of the evaluators. In this study, ten dentists, all approved specialists in prosthetic rehabilitation, evaluated the similarity grade between 10 randomly chosen centrals of the sample on a scale from 1 to 10 (visual similarity). (A) The results of these visually ratings were analyzed by means of MDS (SPSS 14.0: INDSCAL-Procedure, several matrices, weighted model). (B) A second MDS calculation (same settings as before) was proceeded based on the results of the similarity measure (SSV) concerning the same ten selected teeth. "Stress" was used as measure of goodness-of-fit of both MDS procedures (17). Individual weights for both dimensions are displayed as well. This proceeding has the following aims: Firstly the resulting graphical representation (technically called perceptual map) based on visually ratings (A) is used to detect meaningful underlying dimensions interpretable as principle

features of tooth morphology. Practically one has to identify a certain cluster of teeth and compare groups of pooled teeth concerning their differences in morphological feature characteristics. Secondly the perceptual maps based on (A) visually ratings and (B) metrical data of SSV were interpreted concerning their analogy. In this way, information on the coincidence between visual perception and the 3D-measurement of tooth morphology was anticipated. For this reason also Spearman's rho rank correlation coefficient between SSV-data and experts' similarity ratings (concerning same teeth) was calculated. Thirdly displaying of individual dimension weights is to reveal if dimension 1 or 2 is considered to be more important.
All statistical procedures were carried out with SPSS 14.0 (SPSS Inc., Chicago, USA).

Results

Mean shape similarity values (SSV) of symmetric (contralateral) and non-symmetric teeth differed significantly (Mann-Whitney U-Test, $P<.001$) by a factor of 2 (Fig. 2 and Table 1).
Two-dimensional perceptual mapping of (A) visually ratings (Stress 0.29) allows identification of a certain cluster with three groups (i:red triangles, ii:blue squares, iii:green circles) of teeth (Fig. 3). The individual dimension weights are varying but overall, dimension 1 is considered to be more important than dimension 2 (Fig. 4). Mapping of the MDS based on (B) SSV-data (Stress 0.10) is comparable only in parts to mapping of (A) visually ratings (Fig. 3). The correlation between the SSV-values and the similarity rating of the MDS is significant but weak (Spearman's rho rank correlation coefficient 0.328, $P<.05$).

Discussion

By means of a similarity measure, an informative basis for the variability of natural tooth forms was provided. Older studies only use one-dimensional length values for the comparisons of similarity (3, 5). That makes it difficult to determine reference points exactly and causes measurement errors. In addition, one-dimensional metrical parameters are not suitable to describe complex 3-dimensional structures like teeth. When calculating the shape similarity value, no reference points have to be set. This way of comparing tooth forms is technically robust and allows a huge number of comparisons in a suitable time due to its automatic procedure. In contrast to calculating the standard deviation, the new measure includes the deviations in a linear way and therefore does not overestimate outliers with quadratic terms. This reduces errors which may arise from differences on steep inclines or measurement errors from optical scanners. A possible limitation is that only an average value is calculated that does not indicate which areas of two surfaces are coincident or different. However, the results confirm that the new 3D-measure is able to distinct clearly between contralateral and different individual teeth as it is commonly assumed.

In order to explore morphological features which have an impact on visual perception, mapping of MDS based on visual ratings (A) was used. Obviously, teeth pooled in group i have the lowest, teeth in group iii have the highest width-length-ratio (Fig. 3). Hence dimension 1 (x-axis) seems to represent the width-length-ratio as basic characteristic feature. In contrast, the authors were not able to clearly determine the meaning of dimension 2 (y-axis). Possible features might be the curve of the distal incisal angle, the mesiodistal or incisocervical curve, the markedness of the incisal edge, incisocervical grooves, other features or combinations. Differences in experts' individual dimension weights indicate variability of visual perception. But generally dimension 1 is seen to be more important for visual perception. Therefore, the width-length-ratio could be confirmed as a basic feature for the appearance of maxillary anterior teeth. Morphological measures like the one introduced can be used for quantifying the similarity of anterior teeth. It is desirable that such a measure corresponds well with visual perception to give feedback not only about the metrical but also the esthetical fit of computer-assisted design. In this study the perceptual map of (A) MDS based on visual ratings is comparable only in parts to the map of (B) the MDS based on SSV-data (Fig. 3). The correlation analysis between similarity ratings and SSV indicates a weak but significant correspondency, too. Maybe metrical and visual coincidence is only moderate because width-length-ratio is not detected adequately by the measure.

All in all the measure proofed its metrical validity. In contrast a quantification of an esthetic value seems to be difficult to correlate with a morphological one, but the subjective method introduces an interesting way to proceed. For further visual evaluations, concrete pre-selections of potential features and closed questions on morphological characteristics seem to be useful. Better knowledge about visual perception helps improving the morphological measure.

In conclusion, the newly established and consecutively validated 3D-measure SSV may be a substantial step towards a morphometric quality control of CAD/CAM-restorations of anterior teeth. It enables internal feedback about the morphological as well as the esthetical appearance and naturalness of teeth during an automatic reconstruction process, therefore improving the proposals of CAD/CAM-systems and decreasing time for manual post-modelling. Besides that, a new method of analysing the visual perception of teeth is introduced.

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Table 1. Shape Similarity Value (SSV) as 3D-Similarity Measure for Comparisons of the Morphology Between Symmetric and Non-symmetric Pairs.

	Symmetric (A)		**Non - symmetric** (B)	
	n	SSV (μm) *	n	SSV (μm) *
CENTRALS	125	**48** ± 20.26 10.29-147.44	31 000	**98** ± 29.06 30.65-239.60
LATERALS	125	**60** ± 25.53 25.07-138.00	31 000	**106** ± 34.86 35.37-315.16
CANINES	125	**56** ± 21.82 26.83-153.64	31 000	**109** ± 28.81 41.92-260.17

* Values are given as **mean** ± SD, followed by range.

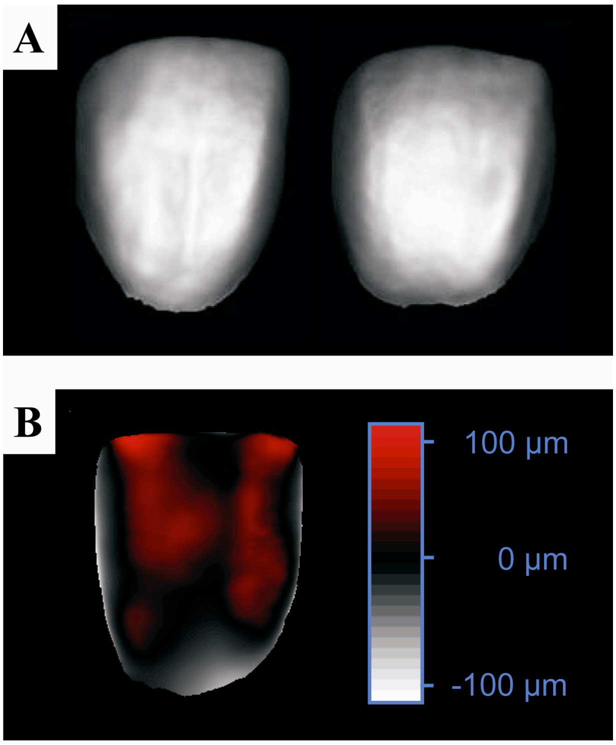
Figure Legends

Fig. 1. (A) Two maxillary central incisors. (B) Difference picture, resulting from superposition of these two central incisors. The difference picture displays local deviations in terms of color. Scale displays differences in z-direction [µm].

Fig. 2. Histograms of maxillary central incisors' shape similarity value (SSV). (A) Symmetric. (B) Non-symmetric.

Fig. 3. Perceptual maps of MDS algorithms. Each tooth is represented by an item in the 2-dimensional space (nr 1-10: number of anterior tooth). (A) Result of MDS based on visual perception of 10 experienced dentists. Cluster of three groups is observable (i:red triangles, ii:blue squares, iii:green circles) (B) Result of MDS based on data of shape similarity value (SSV).

Fig. 4. Individual dimension weights of MDS based on visual rating (A). Triangles represent dental experts (S1-S10). Individuals located below and right of the dashed line consider dimension 1 to be more important.



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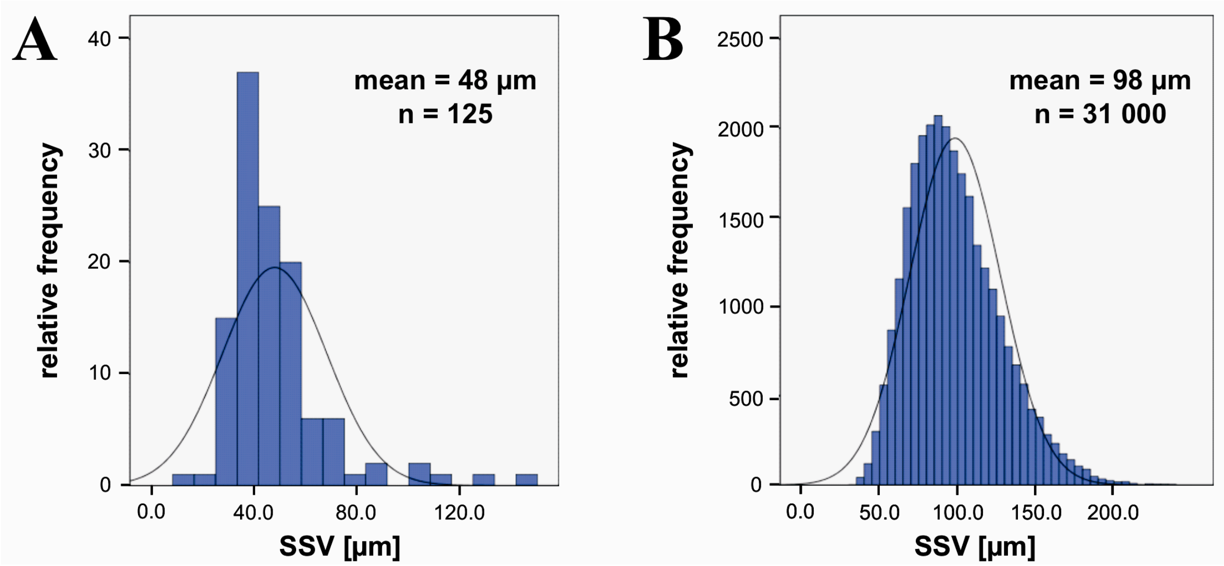

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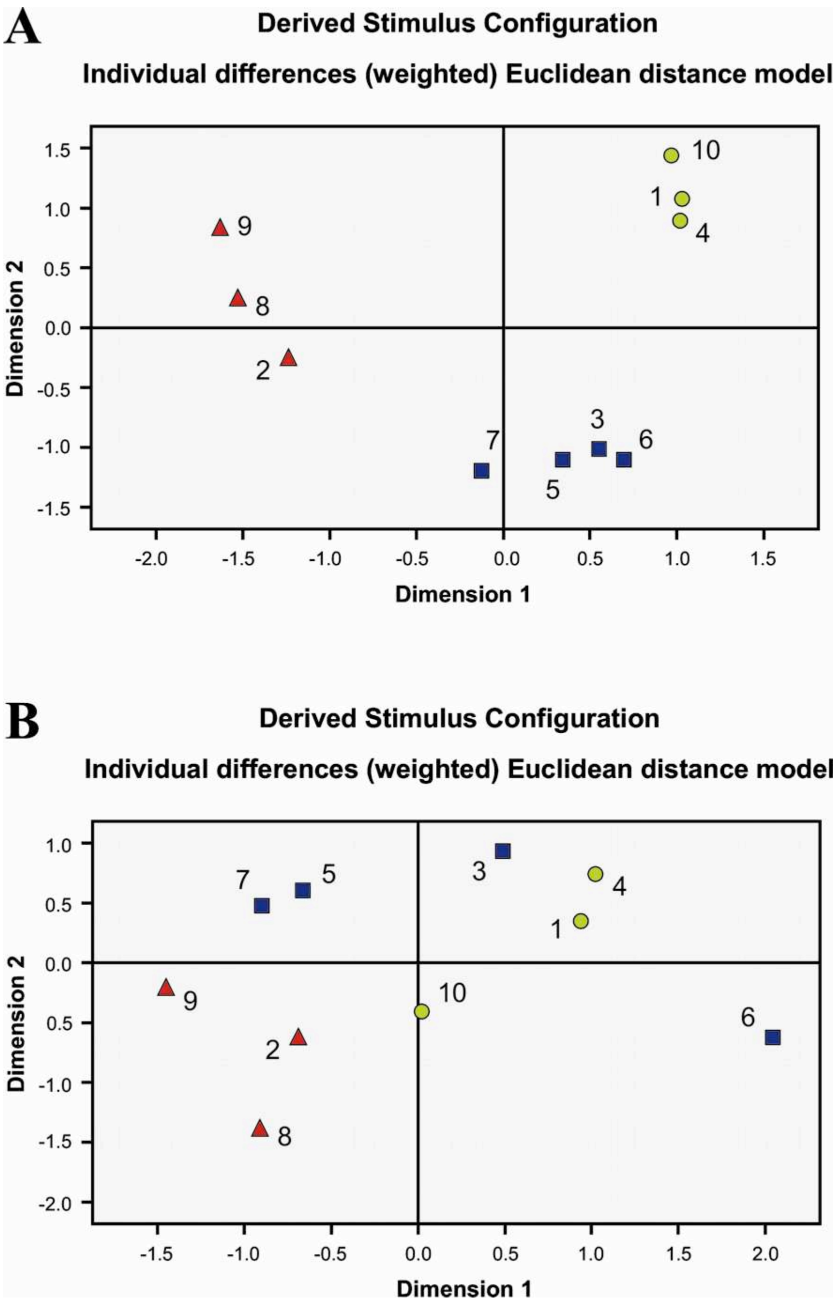

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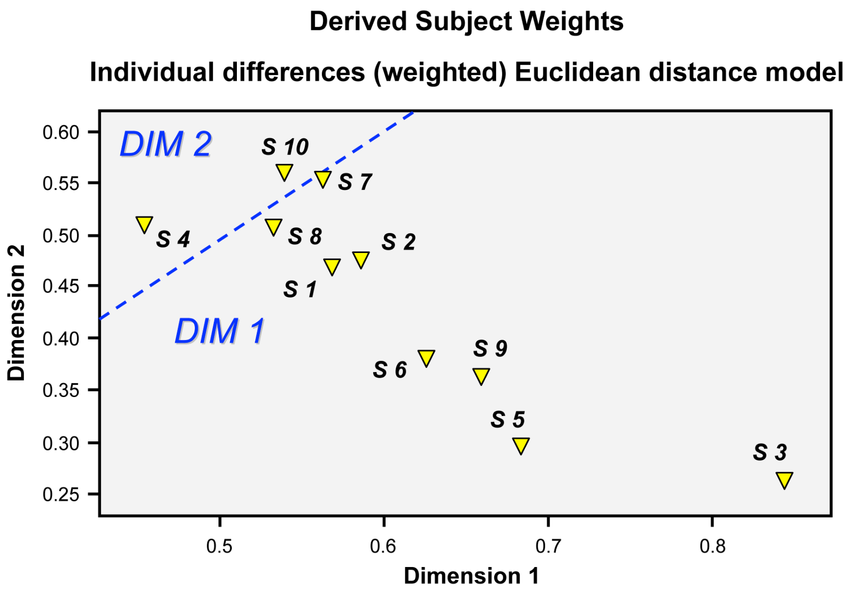

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